Effects of Turbulence Parameterization Schemes in Hydrostatic and Nonhydrostatic Shelf Circulation Models

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LONG-TERM GOALS

To understand the role of small scale turbulent mixing in influencing larger scale circulation processes over the continental shelf.

OBJECTIVES

To evaluate and improve the utilization of turbulence parameterization schemes in hydrostatic and nonhydrostatic shelf circulation models.

APPROACH

The effects of different parameterization schemes for small scale turbulent mixing are being studied by model-model and model-data comparisons. Both hydrostatic and nonhydrostatic models are being utilized. The rationale for the inclusion of nonhydrostatic Boussinesq models is that nonhydrostatic effects are expected to be of first order importance in several flow processes involving energetic turbulent mixing over continental shelves. For that purpose, we are initially adapting and applying a nonhydrostatic mesoscale ocean model developed by Mahadevan et al. (1996a,b). The hydrostatic model being utilized is ROMS (Shchepetkin and McWilliams, 1998).

Initial applications include experiments relevant to three-dimensional flows over the Oregon continental shelf and slope and focus on model-model comparisons. This research is being carried out jointly with Postdoctoral Research associate, Scott M. Durski. The choice of the Oregon shelf is made to facilitate eventual model-data comparisons. Effects of different turbulent parameterization schemes on the model behavior will be assessed and compared to observations. Field measurements of currents, temperature, and salinity will be utilized for comparison of mesoscale shelf flow characteristics while direct measurements of turbulent kinetic energy and turbulent dissipation will be utilized for comparison with predictions of these variables by the turbulence models. Results of these comparisons will be analyzed in an attempt to identify specific shortcomings or strengths in the turbulent parameterization schemes. A complementary objective is to obtain a better understanding of the conditions under which nonhydrostatic models are necessary to adequately represent shelf circulation processes.

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WORK COMPLETED

For studies of the effects of turbulent parameterization schemes in shelf circulation models, we have proceeded with work on two different fronts. These are:

1) Developing a non-hydrostatic modeling capability for shelf flows,
2) Developing an understanding of the hydrostatic solution to shelf flows that potentially could be altered were this approximation not made.

To this end the following work has been completed.

We have explored the potential for applying the nonhydrostatic mesoscale ocean model of Mahadevan (1996) to several basic coastal ocean processes. These include surface and internal solitary waves, upwelling circulation, and shear instabilities. The model has been modified to include the effects of surface and bottom stress and work has been done to implement a semi-implicit representation for vertical mixing. The possible use of other nonhydrostatic models is still being evaluated. An LES model (Skyllingstad and Denbo, 1995) and DNS model (Smyth, 1999) have been obtained to use as a check on the performance of non-hydrostatic models for shelf flows in experiments with idealized geometries.

We have also explored the potential of modifying two hydrostatic models, SCRUM (Song and Haidvogel, 1994) and ROMS (Shchepetkin and McWilliams, 1998), to represent non-hydrostatic phenomena such as solitons. This modification involves an alteration of the hydrostatic vertical momentum equation to incorporate the effects of advection and time rate of change of vertical velocity. So far, the stability of the numerical solution has been an issue. The most recent work has focused on methods to iteratively improve the approximation of the non-hydrostatic term within each time step in hopes of attaining adequate convergence for stability.

We have considered several shelf flows that can potentially be sensitive to the hydrostatic approximation. These include stratified flow over Stonewall Bank (a steep topographic feature located on the Oregon Shelf [Nash and Moum, 2001, Moum and Nash, 2000]),and flow instabilities of upwelling and downwelling fronts and in the bottom boundary layer during downwelling. Each situation has been studied in both two-dimensional and three-dimensional settings with the hydrostatic model ROMS (Shchepetkin and McWilliams, 1998). All 3D experiments are performed in domains that are periodic in the alongshore direction with an open boundary offshore.

In the Stonewall Bank experiments, both steady winds and a simplified single-constituent (M_2) tidal forcing has been examined. A range of approximations for the bathymetry of the bank has been explored, varying from idealized to realistic. The focus of the downwelling experiments has been to determine how the hydrostatic symmetric instabilities observed in previous two-dimensional studies (Allen, 1996) extend in the fully three-dimensional case. For the preliminary simulations, steady wind forcing and constant stratification have been utilized to draw out the phenomena most clearly.

Of the three hydrostatic shelf flows that have been examined, the greatest effort has been spent on achieving an understanding of how upwelling frontal instabilities develop and evolve. Various bathymetries and initial stratifications have been considered with both steady and intermittent wind forcing. Because we are interested in examining the onset of the instability, issues of numerical noise in the model have received particular attention. It was found that implementations in high-resolution

three-dimensional grids of both the Mellor-Yamada level 2.5 closure scheme (Mellor and Yamada, 1982) and the Large, McWilliams and Doney K-profile parameterization (Large et al.,1994), in ROMS were beleaguered with problems causing small scale non-physical perturbations to the density and velocity fields. Several techniques have been utilized to reduce the noisiness of both implementations. Work is continuing on understanding the nature of these numerical instabilities and the best ways to minimize them.

RESULTS

While a variety of interesting preliminary results have been obtained we focus here on those associated with the upwelling frontal instability study. Initial experiments involve the three-dimensional response to a constant wind stress forcing of a stratified fluid at rest over continental shelf topography. One important result that has emerged from this research is that at finite amplitude the alongshore scale of the frontal instability grows significantly in time. Figure 1 a) and b) display snapshots of potential density and across-shore velocity at 5 meters depth on days 5, 7 and 9 of a simulation forced with a steady 0.5 dyne/cm^2 alongshore wind stress. By day 5 a clearly discernible wave-like pattern appears along the upwelling front at a scale of about 7 km. Two days later, the amplitude of the instability has grown and the length scale has increased to roughly 15 kilometers. By day 9, the alongshore scale is approximately 20 kilometers. Figure 1c displays sections of the alongshore-averaged eddy flux of density $<u'\rho'>$, where the brackets denote an alongshore average and primes denote deviation from that average, e.g., $u = <u>+u'$, for the same days. The sections show a region of steadily increasing eddy flux that is primarily confined to a near-surface layer and that moves offshore as the upwelling progresses. The eddy fluxes from the instability consequently occur in the surface layer region affected by the turbulence parameterization. This solution was obtained using the Mellor-Yamada level 2.5 closure scheme. Simulations were also performed with the KPP scheme. The time at which the instability first becomes visible differs between the two schemes but the frontal patterns appear qualitatively similar within approximately 5 days. A quantitative analysis of upwelling frontal instabilities and their dependence on the turbulent mixing parameterization is in progress.

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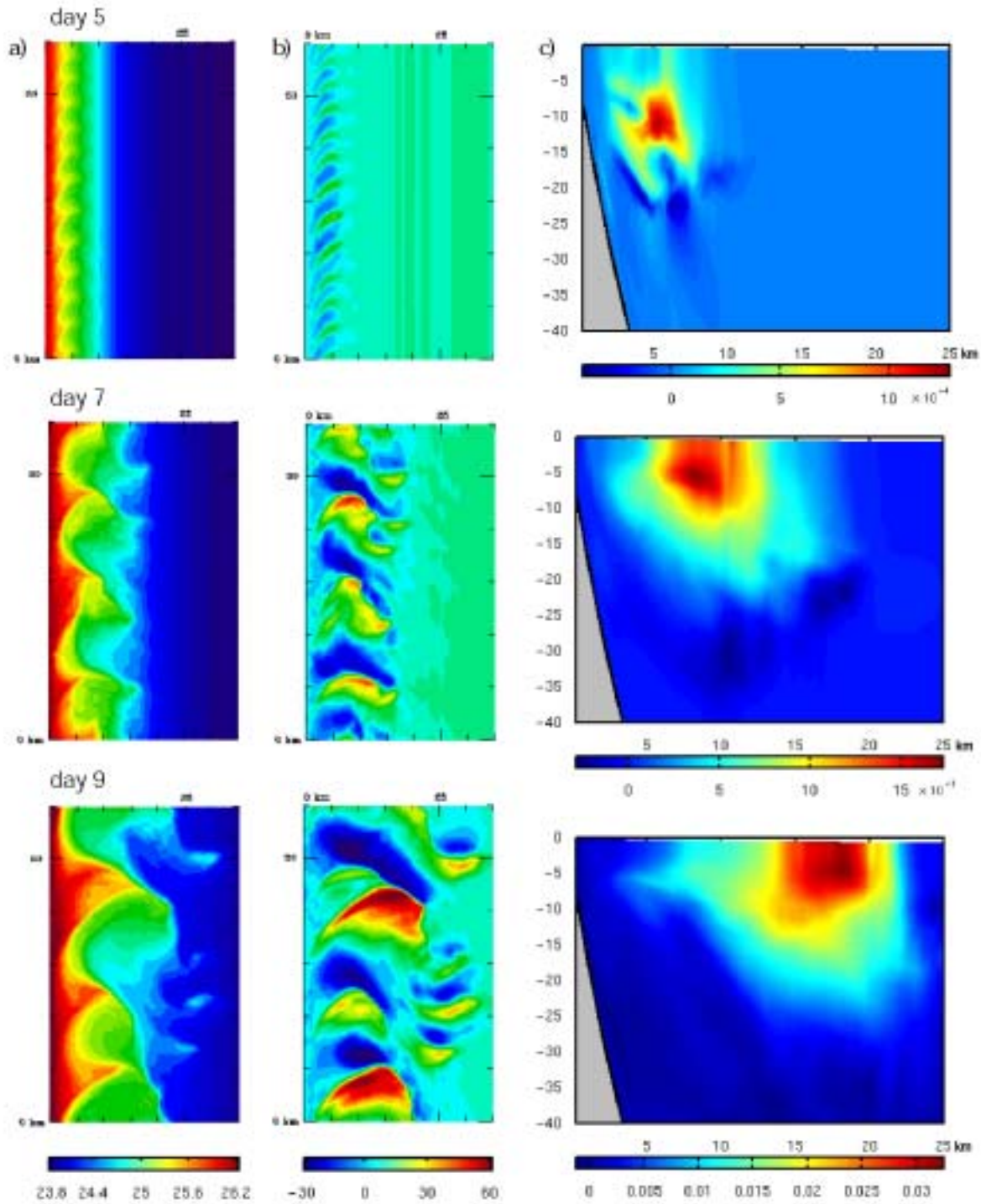
Figure 1. Potential density (a) and across-shore velocity (b) at 5 meters depth on days 5,7 and 9 of a constant-wind-stress upwelling simulation, along with vertical sections of the along-shore-averaged eddy flux of density <u'ρ'>. The potential density and across shore velocity plots show how the along shore scale of the frontal instability increase with time. The eddy flux sections reveal that the flux extends downward from the surface less than 25 meters. Consequently, the flux due to the frontal instability occurs in a region strongly affected by the surface boundary layer turbulence and thus by the turbulence parameterization scheme